NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

ELSEVIER Nuclear Instruments and Methods in Physics Research A 419 (1998) 642–647

High-performance, imaging, thermal neutron detectors[1]

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Abstract

Existing and planned spallation neutron sources require two-dimensional detectors for many experiments. Unlike the requirements for steady-state neutron sources, it is essential that these detectors possess good time resolution to determine neutron energy. A range of detectors based on gas proportional chambers, with low-noise encoding electronics, has been fabricated at this laboratory, with properties well suited for use at spallation sources. These high-performance detectors possess outstanding qualities in terms of dynamic range and stability of both recorded neutron positions and response (efficiency), in addition to normal attributes such as good position resolution, high detection efficiency and insensitivity to γ-rays. We review here some of the major characteristics of the detectors, describe recent advances, and illustrate their high level of performance with neutron scattering results. While relatively few such detectors are required world wide, specialized efforts are required for their development. The additional opportunities provided by new spallation sources will need continued advances in detector performance. © 1998 Published by Elsevier Science B.V. All rights reserved.

Keywords: Thermal neutron detectors; High flux beam reactors

1. Introduction

Determination of molecular and crystal structure in biology, solid state physics and polymer chemistry is an important application of the neutron scattering technique. For example, in structural biology, hydrogen atoms are critical to structural stability and enzymatic function; neutron diffraction provides a unique approach to the study of biological systems by allowing for determination of hydrogen atoms, which are largely unobservable by X-rays. The European Spallation Source and the Spallation Neutron Source in the US are two of the planned, next generation, thermal neutron sources. These new, and existing, spallation sources, require detectors with the usual characteristics of good efficiency, low gamma sensitivity, high rate capability, high position accuracy and stable response. An additional requirement, compared with detectors for steady-state sources, is timing resolution to permit determination of neutron energy. At Brookhaven, we have been developing, for some years, thermal neutron detectors based on wire chambers with ^{3}He, for reactor-based experiments. They are

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[1] This research was supported by the U.S. Department of Energy under Contract No. DE-AC02-98CH10886.

PII: S0168-9002(98)00844-4

equally well suited for spallation sources; here we describe some of their important features.

2. Two-dimensional proportional chambers

2.1. Operating principles

We have designed and fabricated two-dimensional detectors with a wide range of collecting areas, from 5 cm × 5 cm to 50 cm × 50 cm. Common features are an absorption and drift region, followed by the multiwire chamber proper, with position-encoding on each of the two cathodes. Fig. 1 shows a cross-section of the electrode structure, the total gas depth from window to lower cathode typically being about 15 mm. After neutron conversion in the absorption region, primary ionization drifts through the upper cathode wires and creates an avalanche on the anode plane. Induced charge is created on both cathodes, whose interpolating characteristics permit determination of the center of gravity of the anode avalanche with good linearity [1]. A centroid finding technique [2] achieves a high absolute position accuracy and a high position resolution with small avalanche size because of the number of signal nodes on each axis of the detector. With node spacings of order 1 cm, and anode avalanche size of about 0.1 pC (measured in 1 μs), electronic position line widths of well below 1 mm are easily achievable. This most important attribute is not possible in global encoding methods with only two outputs per axis. The relatively small avalanche size is a major reason that this class of detector will operate, with no servicing, for years at a time.

2.2. Position resolution and efficiency

The gas mixture used in these devices comprises ^3He and C_3H_8; the ratio is determined by the efficiency and position resolution required. ^3He has a very high cross-section for thermal neutron absorption (about 5500 b at 2 Å, 24 000 b at 8 Å), the reaction products being given by

$$^3He + n \rightarrow {}^3H + p + 0.764\,MeV.$$

The kinetic energy of the products results in the creation of about 30 000 primary electrons at the neutron conversion point. Because of the finite range of the triton and proton, the centroid of this ionization is displaced from the actual interaction position by about 0.4 of the range of the proton [3]. To achieve resolutions in the millimeter range, a gas with significant stopping power is required for the proton, such as propane. While other gases can accomplish this task, propane is chosen because it has a low sensitivity to γ-rays, and is also compatible with the gas purifier used for these detectors [4]. Fig. 2 shows the calculated position resolution

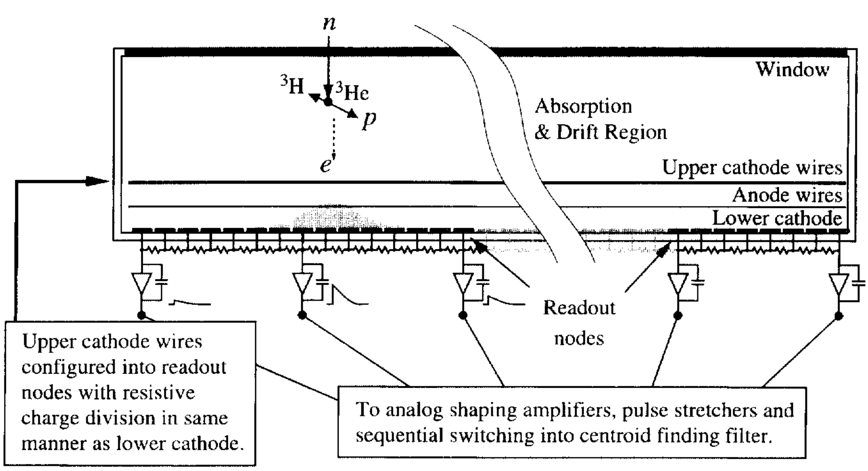

Fig. 1. Schematic diagram of proportional chamber geometry.

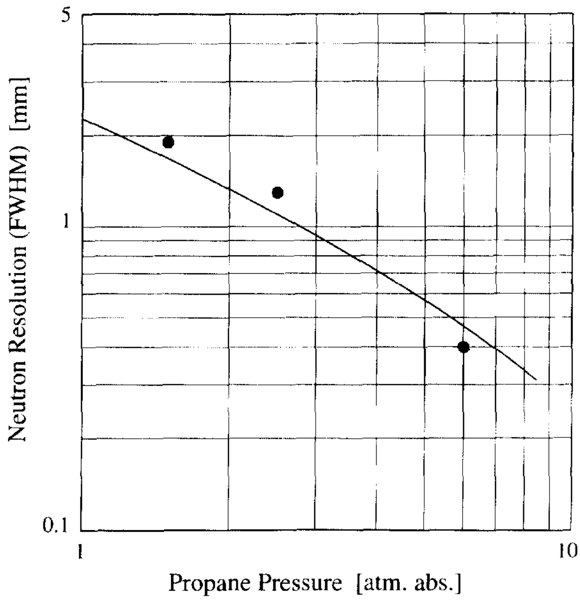

Fig. 2. Position resolution, calculated and measured, with 6 atm. ^{3}He and increasing pressure of propane.

as a function of propane pressure, with a constant additive of 6 atm ^{3}He. The solid circles show position resolution, limited purely by proton range, measured with our detectors using collimated neutron beams. The most recent of these, from a 5 cm × 5 cm detector, is about 400 μm FWHM, which is the best resolution for neutrons ever measured in a gaseous detector [5].

3. Importance of stability

All of the detectors described here are sealed, with an in-line purifier and pump to remove electronegative impurities. This permits long periods of operation of the detector. For example, detectors that were fabricated early in this program, some over ten years ago, have been in use at beam-lines of the High Flux Beam Reactor (HFBR) at Brookhaven with little or no downtime for servicing. These detectors also possess extraordinary levels of absolute position stability and absolute count rate repeatability, features that are virtually unique and therefore permit types of experiment that would otherwise be almost impossible to carry out. In one such study, the growth of crystalline domains in a non-ionic detergent water mixture was investigated at constant temperature by time-resolved, small-angle neutron scattering (using a 50 cm × 50 cm detector at the HFBR) in order to characterize domain fluctuations [6]. Structural oscillations about a meta-stable state are observed at 5 min intervals by recording the intensity and positional shifts of the many tiny Bragg peaks that speckle the Debye Scherrer ring. One of the many time frames recorded over several days is shown in Fig. 3; it is the detector's ability to plot the time course of the intensity and position of the diffraction peaks with such high precision that makes a study of this nature unique. A thorough understanding of the thermodynamics of this bicontinuous phase is essential for further development of similarly constituted materials used as drug delivery vehicles.

4. Recent improvements in wire chambers

4.1. Anode wire modulation

The position response in the axis across the anode wires is usually modulated, with a frequency equal to the pitch of the anode wires. The response, however, is extremely stable, and a smoothing matrix is normally generated by uniform irradiation of the detector. Using a special arrangement of anode and upper cathode wires which have the same pitch, are parallel and in registration with each other [7], we have demonstrated a significant reduction in anode wire modulation in X-ray detectors. The new wire arrangement has now been demonstrated in a 20 cm × 20 cm neutron detector, and the result of uniform irradiation across the wires, in a part of the detector, is shown in Fig. 4. The modulation has been reduced by at least a factor two.

4.2. Parallax reduction

Parallax broadening in a conventional gas detector occurs in the parallel field of the complete depth of the detector, where signal electrons drift perpendicular to the electrodes. To eliminate parallax, signal electrons should move along radial field

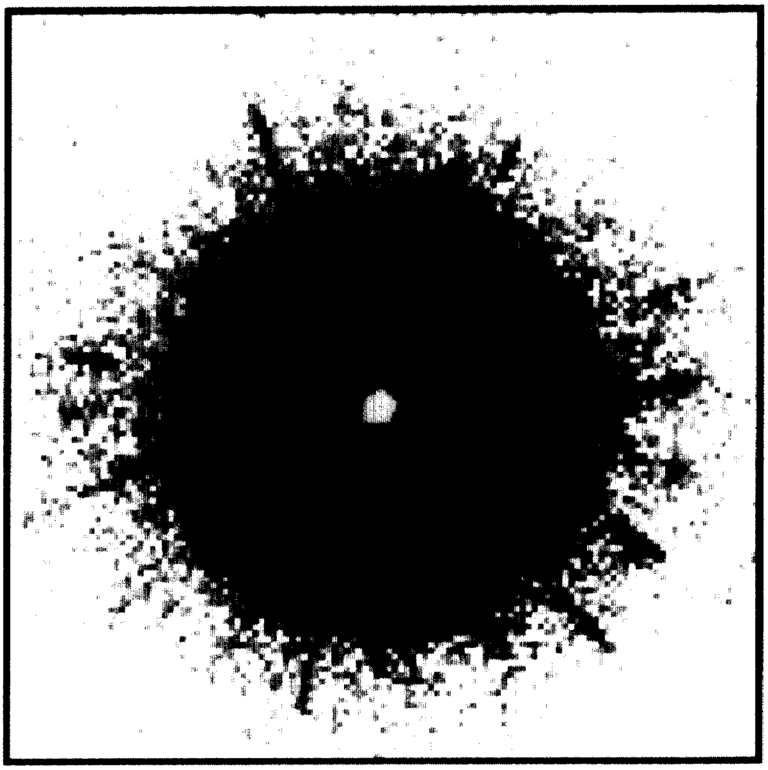

Fig. 3. Small-angle scattering diffraction image, detailing many tiny Bragg peaks in a Debye Scherrer ring, taken with a 50 cm × 50 cm detector.

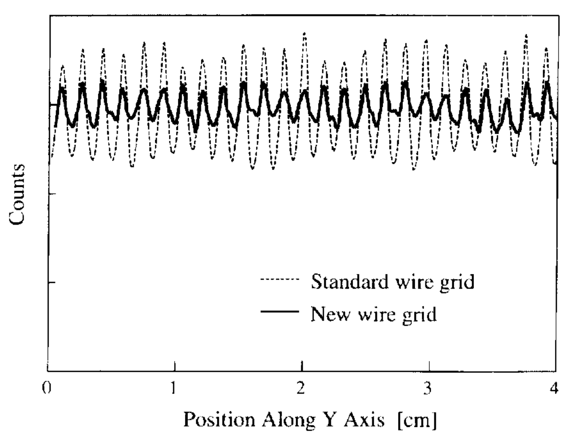

Fig. 4. Anode wire modulation with standard wire array (dashed line) and with new wire array (solid line).

lines that intercept at a point coinciding with the position of the sample under study. Such an ideal, parallax free field is spherical, and cannot be achieved in these detectors because the upper cathode is necessarily at a constant potential. However, the potential of the entrance window can be changed in a radially symmetric way to minimize the effect of parallax. This is achieved by placing conducting annuli on the inner side of the window, and applying a progressively decreasing negative potential from the center ring to the outside ring. Excellent results have already been demonstrated for X-rays [8] and we are currently developing the technique for neutron systems where the incident angle is large enough to justify its use.

5. Spallation source applications

All of the attributes so far described are equally suitable for experiments at reactor or spallation neutron sources. For the latter, timing resolution is also required, which is determined by the time

Table 1

Position resolution (FWHM)	< 0.4–2 mm
Resolution elements	128 × 128–4096 × 512
Size	5 × 5 cm^2–150 × 20 cm^2
Wavelength range	1–20 Å
Detection efficiency	50–80%
Counting rate (one module)	2 × 10^5 sec^{-1} sustained
Integral non-linearity	2 × 10^{-4} to 10^{-3}
Absolute position accuracy	30–100 μm
Stability of origin	< 50 μm
Stability of efficiency	< 1%
Differential non-linearity	± 3%
Dynamic range	Single neutron counting
Timing resolution (rms)	< 1 μs

taken for electrons to travel from the window to the avalanche region (since a neutron may be absorbed anywhere in the gas depth). GARFIELD [9] and MAGBOLTZ [10] (drift chamber simulation and electron transport programs, respectively) can be used to compute electron drift velocity, determined to be about 1 cm/μs for a field of 1 kV/cm in our typical gas mixtures. Thus, an rms time resolution of 1 μs or better is achievable. A useful summary of the operating characteristics of gas filled detectors for thermal neutrons is given in Table 1.

We are now designing and fabricating a large, curved detector for protein crystallography studies at the LANSCE pulsed spallation source at Los Alamos National Laboratory. From a single neutron pulse, the detector, placed about 16 m from the neutron creation point, receives higher energy neutrons first, lower energy ones last; thus, time acts as a monochromator. For example, in these experiments the wavelengths of interest range from 1–5 Å, corresponding to a time of flight of about 4–20 ms. The experimenter requires a wavelength bandwidth of 0.15 Å per time slice, which corresponds to about 600 μs. Therefore, the detector timing resolution of about 1 μs will define very clearly the boundaries of each time slice. A large collecting area is important for this type of experiment. The detector under construction will have an angular coverage of 120° × 16° with a sample to detector distance of about 70 cm. It is divided into eight identical detector modules, each of which has its own 2-D position encoding electronics, for increased rate capability. The two techniques outlined in the last section will be used to improve this detector's performance; parallax in the axis along the 120° arc will be eliminated by using a single curved aluminum pressure vessel, shown in Fig. 5, in which all eight wire frame modules are housed. As in our

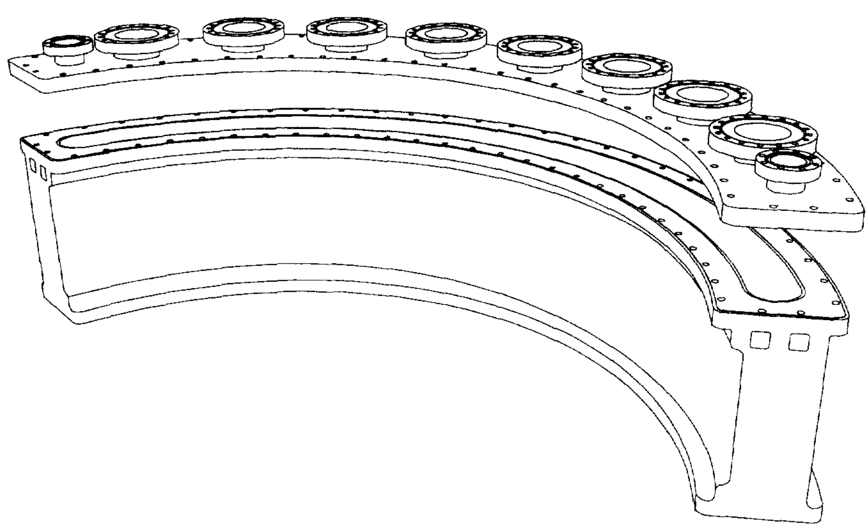

Fig. 5. Detector pressure vessel for 120° curved detector. Entrance window is about 1.5 m along the arc, and about 20 cm high. Conflat flanges on main, top flange provide bulkhead connections for services to the eight wire frame modules.

previous 2-D neutron detectors, the position encoding will be performed by interpolating cathode strips with resistive charge division, yielding a neutron resolution of about 1.3 mm FWHM in both directions. A digital centroid finding position decoding system is being developed to increase the counting rate beyond that of the existing centroid finding filter; this will provide a rate capability of several MHz for the entire detector.

Acknowledgements

The authors acknowledge the advice and support of Benno Schoenborn at Los Alamos, and Dieter Schneider and Anand Saxena at Brookhaven, in this detector development program. The authors are very grateful to Dieter Schneider for providing the small-angle scattering diffraction image.

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